Vortex Identification - Applications in Aerodynamics: A Case Study

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ABSTRACT

An eigenvector method for vortex identification [1] has been applied to recent numerical and experimental studies in external flow aerodynamics. It is shown to be an effective way to extract and visualize features such as vortex cores, spiral vortex breakdowns, vortex bursting, and vortex diffusion. Several problems are reported and illustrated in the accompanying video. These include: disjointed line segments, detecting non-vortical flow features, and vortex core displacement. Future research and applications are discussed, such as using vortex cores to guide automatic grid refinement.

1 INTRODUCTION

Investigators have used the concept of swirling flow as one of the means of locating vortices in 3-D discretized vector fields. These features have traditionally been identified by studying vector fields that have been mapped onto geometric cuts or by seeding massless particles and looking for helical patterns. These procedures can be laborious, especially for large and/or complex flows, and the time taken using these methods is further exacerbated by unsteady (transient) simulations where there may be hundreds of time steps of the vector field.

Various tools and algorithms have been developed by many investigators, including Moin and Kim [2] [3], Villasenor and Vincent [4], Globus, Levit, and Lasinski [5], and Banks and Singer [6] [7] and Jeong and Hussain [8]. For various reasons, all of these schemes fail to find vortices in an automated and robust manner.

To reduce the analysis time of large data-sets, automated assistance is required to point out areas of potential interest within the flow field. This should not require a heavy compute burden (the visualization should not significantly slow down the solution procedure for co-processing environments [16]). An algorithm of this type, based on eigenvector analysis, was developed by Sujudi and Haimes [1]. The scheme works on a cell by cell basis, lending itself to distributed and parallel processing. It does not use any serial operations, unlike techniques that involve integration, and is deterministic, fully automatic (no 'parameters'), and creates an effective visualization with minimal output.

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This paper presents applications of the eigenvector method to recent aeronautical studies at NASA Ames Research Center. Its usefulness for detecting flow features such as vortex cores, vortex bursts, spiral vortex breakdowns, and vortex diffusion is highlighted. Problems with the technique are also addressed, and future research needed to improve the resulting visualizations is identified.

2 THEORY

Critical points are defined as points in a vector field where the streamline slope is indeterminate and the velocity is zero relative to an appropriate observer [9]. According to critical point theory, the eigenvalues and eigenvectors of the rate-of-deformation tensor $\partial v_i / \partial x_j$ evaluated at a critical point define the flow pattern about that point. Specifically, if the eigensystem displays one real and one pair of complex-conjugate eigenvalues, the flow forms a spiral-saddle pattern. The two eigenvectors corresponding to the pair of complex-conjugate eigenvalues define the plane on which the flow swirls, while the eigenvector corresponding to the real eigenvalue points in the direction about which the flow spirals.

The above criteria can be used to find the center of swirling flows located at critical points. However, critical points may only bound a vortex line, but there is obviously swirling flow at non-critical points. Fortunately, a similar method can be applied in these cases. At a non-critical point with the necessary eigenvalue combination (i.e., one real and two complex conjugates) the velocity in the direction of the eigenvector corresponding to the real eigenvalue (the axis of rotation) is subtracted from the local velocity field. The invariance of the eigenvectors' directions with respect to a Galilean transformation ensures that the resulting flow will have the same principal directions. If, in this local vector field, the velocity at the point being considered is zero, then the point must be at the center of the swirling flow. By decomposing all mesh elements into tetrahedra, and assuming a locally linear velocity field, a constant rate-of-deformation tensor can be evaluated. If an axis of rotation pierces a tetrahedron, a line segment is constructed between the points where it intersects the faces. For the details of this implementation see Sujudi and Haimes [1]. This scheme is not unlike that suggested by Sawada[10].

The end result is the distillation of the entire vector field into a series of disjoint line segments. The data compression is usually more than two orders of magnitude and therefore easy to store and quick to display.

3 PROBLEMS

Several problems have been identified with this approach. These include:

Not producing contiguous lines. The method described above, by its nature, does not produce a contiguous line for the vortex core. This is due to two reasons. (1) The algorithm requires that all elements be subdivided into tetrahedra so that the vector field can be represented by a linear interpolation function. For elements other than tetrahedra, the native interpolation functions are non-linear. Subdividing pyramids, prisms, hexahedra and higher-order elements into tetrahedra produces a piecewise linear approximation to a non-linear function. (2) The eigenvectors of a linear vector field are constant and will therefore be discontinuous at shared faces between tetrahedra. During the method, when the real eigenvector (from each cell) is subtracted from the vector values at the shared nodes, this produces a slightly different velocity field for that shared face. Therefore a different location may be found where the axis intersects the face.

Locating flow features that are not vortices. The eigenvector method finds centers of swirling flow (of which a vortex core is the prime example). There are other situations where swirling flow is detected, specifically in the formation of boundary layers. Most implementations of this technique do not process cells that touch solid boundaries to avoid producing line segments in these regions. But this does not always solve the problem. In some cases (where the boundary layer is large in comparison to the mesh spacing) this boundary layer generation is still found. A prime example can be seen in the video of the rolling delta wing along the fuselage.

Sensitivity to other non-local vector features. Critical point theory gives one classification for the flow based on the local flow quantities. 3D points can display a limited number of flow topologies including swirling and spiraling flow, expansion and compression (with either acceleration or deceleration). The flow outside this local view may be more complex and have aspects of all of these components. The local classification will depend on the strongest type. Also if there are two (relatively strong) axes of swirl, the scheme will indicate a rotation that is a combination of these rotation vectors based on the relative strength of each. This has been reported by Roth and Peikert [11] where the overall vortex core strength was not much greater than the global curvature of the flow. The effect of the combined curls was that the vortex core was displaced from its true center.

4 APPLICATIONS

4.1 Numerical/Experimental Study

Both numerical simulations and wind tunnel tests are routinely run to study new aircraft designs. The comparisons drawn between the numerical and experimental results are typically based on quantitative data, such as the maximum difference in core-centerline velocity, which provide relatively little insight. The most widely used technique for finding the vortex core is to construct contours of cross-flow velocity, i.e., the velocity in the plane perpendicular to the free-stream or onset flow (Fig. 1a). The vortex core is located at the points where the cross-flow velocity is a minimum. The main problem with this technique is that the minimum is difficult to detect when the vortex is close to the wing. It is in these regions where aeronautical engineers have found the vortex core extraction technique to be most useful, since they can trace a vortex to its origin in the boundary layer.

Comparisons between numerical and experimental results are traditionally done using side-by-side images. Figures 1a and 1b show results from numerical and experimental studies of a wing-tip vortex [12]. The experimental data was acquired with a hot-wire anemometer in a 32x48 inch wind tunnel. Velocities were sampled on an 11x21x29 grid, with the closest spacing in the wing boundary layer and the primary vortex core. The CFD grid contained more than 370 times as many points with dimensions 115x189x115. Note that the low resolution of the experimental data-set produces obvious artifacts when rendering color contours and makes it difficult to compare the results. By overlaying the 3D vortex cores in the same image (shown in the video), scientists have found it easier to draw comparisons between the two types of data. In this case, the velocity along the vortex core was shown to be within 3% of the experimental results.

4.2 Spiral Vortex Breakdown

The ability to fly and maneuver at high angles of attack has distinct advantages in aerial combat. However, the aerodynamics and control responses in the nose-up attitude are very different from those in level flight. Numerical simulation is being used to study aircraft maneuver aerodynamics in this regime. The video shows one such simulation -- a delta wing aircraft undergoing a roll at α=30 deg. It shows two vortices being shed off the nose of the delta wing. The scientist who studied this flow initially used time-accurate particle tracing to visualize the vortices (Fig. 2a).

To make an effective visualization with particle traces, the seed locations had to be found by trial and error. The sudden dispersion of particles aft of the leading edge revealed that vortex breakdown occurred on both sides of the wing. The vortex cores extracted from this data-set (Fig. 2b) also revealed the vortex breakdown, although no human intervention was needed. This type of breakdown is actually called a spiral vortex breakdown for obvious reasons, and is clearly visible in the video. The vortex cores were extracted independently from each of the 600 solution files, and played back sequentially to produce the animation. In total, this data-set required over 13 gigabytes of storage, while the vortex cores required less than one percent of this.

4.3 Locating a Vortex Burst

Vortices can produce undesirable effects such as reduced lift, control buffeting, audible noise and airframe vibration. The latter effect caused a serious problem on the F/A-18 fighter aircraft when flying at a high angle of attack (α=30 deg). The vortical flow which originates at the front of the wing from the leading edge extension (LEX) was found to impact on the vertical fins and lead to early structural failure (Fig. 3). To remedy this problem, a small trapezoidal plate, called a fence, was attached to the LEX to disturb the airflow and reduce the tail buffeting. The fence for the F/A-18 was developed through wind-tunnel experiments, but the underlying physics was not well understood. CFD simulations are now being done to study this phenomenon [13].

A crucial feature that the aeronautical engineers were looking for in the CFD simulation was the location of the vortex burst. This occurs where there is flow reversal, i.e., the air travels upstream. The location of vortex burst is characterized by a significant change in the direction of the vortex core. This can be readily seen in the accompanying video. It shows that the core remains almost stationary up until it reaches the fence, after which the core itself begins to spiral.

The vortex cores extracted from this data-set revealed many other interesting features in this flow, such as the vortices separating off the leading edge flap and the vortices entering the engine intakes. Although these were not relevant to this study, these are important to aircraft designers in that they could have a negative impact on maneuverability and on the engine's performance.

The complex geometry of the F-18 was modeled using a collection of 14 separate grids containing 1.7 million grid points. A total of 304 time steps data were saved during the simulation which required 10 gigabytes of disk space. The vortex core geometry required only 180 megabytes of storage.

4.4 Vortex Diffusion

The vortex core detection technique is being applied to solve one of the most challenging problems in rotorcraft CFD: accurate prediction of the rotor wake. The rotor wake is the disturbed flow that is left behind as a rotor blade cuts through the air. The wake rolls up into vortices near the blade tips due to the pressure differences caused by the moving rotor. A major problem with CFD simulations of rotorcraft is that the tip vortices diffuse too quickly due to inadequate grid resolution. Adaptive grid refinement schemes [15] have been partially successful in capturing these vortices, although inadequate grid resolution around the vortex core still causes discrepancies from experimental results.

Fig. 4 shows the vortex cores for a helicopter rotor in hover. The mesh used in this simulation was refined based on the vorticity magnitude. This turned out to be a poor criterion for mesh refinement because the high vorticity magnitude near the rotor tip leads to too many points being inserted in that region and too few in the downstream wake. It can be seen in the visualization that the vortex cores, which originate at the rotor tips, progressively diffuse as they are left behind in the rotor wake. This diffusion is reflected in the coherence of the line segments, i.e., they become more disjointed as the vortex weakens. Experimental results indicate that the trailing vortex from the retreating blade should interact with the advancing blade. In Fig. 4, the grid is sufficiently refined so that there is evidence of this blade-vortex interaction. However, the mesh refinement technique used in this simulation did not completely capture the vortex core, as can be seen in the visualization. Accurate prediction of the blade-vortex interaction is important because it is responsible for most of the audible noise produced by rotorcraft.

5 CONCLUSIONS AND FUTURE WORK

The eigenvector approach [1] has proven to be an effective technique for locating vortex cores in many real-world applications. However, the problems outlined in section 3, such as the appearance of discontinuous line segments and the influence of a curling flow, require that the underlying theory be revisited.

Discrimination and isolation of important vortex cores is another area that needs addressing. Presently, all the vortex cores are extracted from a given data-set, which produces an excessive amount of data in very complex flows. In the case of the F/A-18, the majority of the vortex cores were irrelevant to the study and cluttered the visualization.

The vortex diffusion problem encountered in the rotorcraft simulations will be tackled by linking the vortex core extraction code with an unstructured grid adaptation code [15]. The vortex cores will be used to guide the grid generation by identifying the regions of the grid that need refining or coarsening. This process will occur automatically during the flow computations.

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